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g-2 of the Muon

After 10 years still a puzzle for the now consistent theory – The Brookhaven experiment moves to Fermilab

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Abstract The experimental value a_μ^{exp} for the muon magnetic anomaly measured at the Brookhaven National Laboratory (BNL), Upton, USA, and the latest theoretical value a_μ^{theo} based on a number of calculations and auxiliary experiments differ today by 3.3 standard deviations. Discrepancies between different independent approaches towards the theoretical value could recently be removed and had yielded a consistent value for a_μ^{theo}. At the Fermi National Laboratory (Fermilab), Batavia, USA, a new experiment has been approved which aims to improve the present experimental uncertainty by a factor of about five. At this level the muon magnetic anomaly is superior in sensitivity to, e.g., LHC concerning tests of several speculative models beyond standard theory. The new experiment relies in the essential parts on concepts proven at BNL such as a muon storage ring at 1.45 T field to store muons at 3.1 GeV/c momentum and field magnetometry based on NMR in water. At Fermilab predominantly a significantly higher number of muons can be exploited.

Keywords Muon magnetic anomaly · Standard model test · New physics search

1 Introduction

The magnetic anomaly of leptons is the relative deviation of the leptons magnetic moment from the Dirac value two. It can be very accurately calculated [1–3]. The by far dominating contribution arises from electromagnetic interactions and can be calculated within the framework of Quantum Electrodynamics (QED). The main differences between the leptons arise from their mass differences. The sensitivity of

On behalf of the muon g-2 collaboration E989 at Fermilab.

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the magnetic anomaly to other than electromagnetic interactions increases with the square of the mass of the lepton. Whereas for the electron other interactions are no reason of concern at the present level of accuracy in theory and experiment, the muon, on the contrary, is very sensitive to other interactions at this level. It is even sensitive to potential new, yet unknown interactions, which could show up in vacuum polarization loops through new particles characteristic for these new interactions. Therefore the muon magnetic anomaly is a calibration point for our theoretical understanding of the fundamental interactions. Precise measurements can provide limits on potential new interactions or hints to new physics [4–7].

The theoretical value a_μ^{theo} for the muon magnetic anomaly is composed of a value a_μ^{SM} that can be calculated within the present Standard Theory and a potential contribution a_μ^{NP} from new interactions outside of the Standard Model in particle physics:

$$a_\mu^{\text{theo}} = a_\mu^{\text{SM}} + a_\mu^{\text{NP}} \qquad \text{, where} \tag{1}$$

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{strong}}. \tag{2}$$

a_μ^{SM} consists of three parts which can presently be determined to sufficient accuracy within the Standard Model. They arise from electromagnetic interactions a_μ^{QED}, from weak interactions a_μ^{weak} and strong interactions a_μ^{strong}.

A manifest deviation of the experimental value a_μ^{exp} from the Standard Theory value a_μ^{SM} would indicate the presence of physics beyond the Standard Model, which is searched for with various approaches in high energy physics, such as, e.g., experiments at LHC or in dedicated precision experiments at lower energies, such as searches for permanent electric dipole moments [8], or violations of fundamental symmetries [9–12].

The present Standard Model is an excellent description of all known and confirmed physical processes, however, it lacks in various aspects a deeper explanation of physical phenomena beyond their successful and bare description. A number of speculative theories were invented in order to provide deeper explanations for features in nature not fully explained in the Standard Model like, e.g., the mass hierarchy of fundamental fermions or the number of particle generations. Those speculative theories which in themselves are fully consistent, however, share the lack of experimental verification or even any realistic evidence, yet. We have as examples of such models Supersymmetry, LeftRight Symmetry, Technicolor, Universal extra Dimensions, Littlest higgs with T-parity, two Higgs doublets and shadow Higgs, which all could give rise to a small contribution $\Delta a_\mu^{\text{new}}$ to the muon magnetic anomaly a_μ. Larger values of $\Delta a_\mu^{\text{new}}$ could arise from, e.g., Randall Sundrum models and Models with additional light bosons, which could affect electromagnetic interactions and which are difficult to study at LHC (see e.g. [1]).

2 Situation of theory

The hadronic contributions to a_μ^{theo} have been carefully investigated by different theoretical groups using input from a number of experiments (see for details [1] and

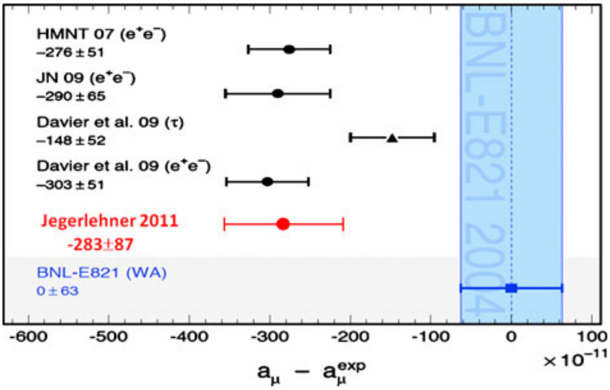

Fig. 1 The calculations of hadronic corrections to a_μ agree now within their uncertainties [13]. The value of Davier et al. 09 (τ) does not yet include all neccessary terms

references therein). The most severe problem which arose in the past decade was the fact that the contributions from strong interactions to a_μ^{theo} were calculated and gave two different results, depending on the chosen route and experimental input. Calculations exploiting electron and positron annihilation into hadrons produced different results from those which were using hadronic τ-decays. It was a major step forward when it was shown by Jegerlehner that terms had been omitted in evaluations involving τ-decays (see Fig. 1). These terms relate to isospin breaking when calculating the hadronic contributions using experimental data from hadronic τ-decays in the region $\sqrt{s}$ around 1 GeV. At this point both values agree satisfactorily and as a consequence there exists one single reliable theoretical value [13]

$$a_\mu^{\text{theo}} = 11\,659\,179.7(6.0) \cdot 10^{-10}. \tag{3}$$

3 Muon magnetic anomaly at Brookhaven National Laboratory

The experiment at the Brookhaven National Laboratory (BNL) [4–7] employed a superferric 7.112 m diameter magnetic storage ring at 1.45 T field to store muons at 3.1 GeV/c momentum, which were injected with longitudinal polarization into the storage volume. The experiment has measured the muon magnetic anomalies for both possible signs of charge. Electrons (positrons) from the decay $\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}$ ($\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$) were detected in calorimeters consisting of scintillating fibers embedded in lead as a function of time. The experiment determined the muon spin precession frequency ω_a in a homogeneous magnetic field measured and mapped through the NMR frequency of protons in water ω_p [14]. Together with the ratio of muon magnetic moment and proton magnetic moment (as determined from muonium spectroscopy [15]), this provided for a determination of the respective magnetic anomalies. They are

$$a_\mu^+ = 11\,659\,204(7)(5) \cdot 10^{-10} \quad (0.7\text{ppm}) \quad \text{and} \tag{4}$$

$$a_\mu^- = 11\,659\,214(8)(3) \cdot 10^{-10} \quad (0.7\text{ppm}), \tag{5}$$

Table 1 The error budget was continuously improved in the course of experiment E821 at BNL. We also show the estimated uncertainties for the new experiment P989 at Fermilab

Uncertainty [ppm]	1998	1999	2000	2001	E821 final	P989 goal
Syst. magn. field ω_p	0.5	0.4	0.24	0.17		0.07
Syst. anom. precession ω_a	0.8	0.3	0.31	0.21		0.07
Statist. uncertainty	4.9	1.3	0.62	0.66	0.46	0.10
Syst. uncertainty	0.9	0.5	0.39	0.28	0.28	0.10
Total uncertainty	5.0	1.3	0.73	0.72	0.54	0.14

Table 2 The evolution of systematic uncertainties of ω_a. Expected improvements due to Fermilab beam structure and improved detectors and electronics are indicated by $^{(*)}$

Uncertainty [ppm]	1999	2000	2001	P989 goal
Pile-up	0.13	0.13	0.08	$0.04^{(*)}$
Accelerator background	0.10	0.10	0.015	
Lost muons	0.10	0.10	0.09	$0.02^{(*)}$
Timing shifts	0.10	0.02	0.02	
E-field, pitch	0.08	0.03	0.06	0.03
Fitting, binning	0.07	0.06	0.06	
Coherent betatron oscillations	0.05	0.21	0.07	0.04
Beam debunching	0.04	0.04	0.04	
Gain change	0.02	0.13	0.13	$0.02^{(*)}$
Total	0.3	0.31	0.21	0.07

and they appear to agree very well for both signs of charge. Here the first uncertainty is statistical and the second systematic. With the assumption of CPT being a good symmetry we can combine them to receive

$$a_\mu = 11\,659\,208(6) \cdot 10^{-10}(0.5\text{ppm}). \tag{6}$$

This experimental value differs from the latest theory value by 3.3 standard deviations. The uncertainties in the experiment (see also Table 1) are mostly statistical. Therefore, a new experiment will mostly need to record significantly more muon decays.

In addition to the magnetic anomaly, the experiment has provided a new limit on the muon electric dipole moment at $d_e < 1.8 \cdot 10^{-19} e\,\text{cm}$ (95% C.L.) [16]. Further, bounds on potential CPT and Lorentz invariance violating terms [17] in a Standard Model extension [18, 19], which surpass previous bounds for muons [20], could also be extracted.

4 Muon magnetic anomaly at Fermilab

The muon g-2 experiment will now move from BNL to Fermilab [21]. The new experiment aims for a 5-fold improvement over the BNL result. The ring magnet, the central device, is presently being dismantled at BNL and it will be reinstalled in a new building at FNAL. In particular the some 15 m diameter special manufactured magnet coils need to be shipped from the Long Island Sound to Lake Michigan and airlifted at both ends of the journey between the nearest port and the respective national laboratories.

In the new experiment the positron(electron) detectors and the electronics will take advantage of new technology which became available since the BNL

Table 3 The evolution of systematic uncertainties of ω_p

Uncertainty [ppm]	1999	2000	2001	P989 goal
Absolute calibration	0.05	0.05	0.05	0.05
Calibration of trolley	0.20	0.15	0.09	0.06
Trolley field measurement	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.15	0.10	0.07	0.06
Inflector fringe field	0.20			
Muon distribution	0.12	0.03	0.03	0.02
Other	0.15	0.10	0.10	0.05
Total	0.4	0.24	0.17	0.11

experiment. A major advantage over the BNL experiment will be the new beamline providing a much cleaner muon beam to the experiment due to its significantly larger length. This essentially reduces hadronic beam contamination and will enable starting the measurement cycles much earlier than at BNL, where a delayed start of positron recording was needed to circumvent nonlinearities in the detectors which were gated to avoid the flashes originating from the hadronic beam contamination. The expected improvements on the systematic errors on the anomaly frequency ω_a are given in Table 2.

The magnetic field measurement system has been designed for BNL with sufficient base accuracy to stand also the challenges of the new experiment. This narrow band pulsed NMR system [14] only needs some modifications in the operating procedures such as more frequent measurements and some fixes of broken parts to achieve the prospected accuracy (see Table 3). The basic concept will be maintained and all the crucial parts of the equipment will be refurbished. Additional measures will be taken for cross checking and calibration. As an example, some of the 360 fixed probes distributed around the ring will be relocated to strategically better suited locations. A second absolute calibration method is being considered in which nuclear magnetic resonance in optically pumped ^{3}He gas is used.

The collaboration and the laboratory are confident, that an improved value for a_μ can be available available within about half a decade. There is a robust potential [22] to either substantiate or disfavour the present 3.3 standard deviation difference between the Standard Model and the experimental value.

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